Letter of Interest: Neutrino Oscillation Experiments Beyond MINOS and MiniBooNE

June 8, 2001

Y-C. Chen
Institute of Physics, Academia Sinica, Nanking, Taipei 11529

D. Ayres, E. Berger, T. Fields, M. Goodman, R. Holt, T. Joffe-Minor, H. Johnstad
D. Krakauer, J. Norem, L. Price, D. Reyna, R. Talaga, J. Thron, C. Zachos
Argonne National Laboratory, Argonne, IL 60439

E. Kearns, J.L. Stone, L.R. Sulak, C.W. Walter
Boston University, Boston, MA 02215

O. Benary, E. O'Brien, J. Gallardo, R. Fernow, S. Kahn, R. Palmer, Z. Parsa
I. Stumer, B. Viren, M. Yeh, Y. Zhao
Brookhaven National Laboratory, Upton, NY 11973

S. Koutsoliotas
Bucknell University, Lewisburg, PA 17837

B. Choudhary, J. George, D. Michael, C. Peck
California Institute of Technology, Pasadena, CA 91125

B. Autin, A. de Gouvea, C. Johnson
European organization for nuclear research (CERN), CH-1211 Geneve 23, Switzerland

L. Bugel, J. M. Conrad, B. T. Fleming, J. Formaggio,
L. Coney, B. Galea, M. Sorel, W. Willis, E. D. Zimmerman
Columbia University, Nevis Labs, Irvington, NY 10533

A.A. Petrov
Laboratory of Nuclear Studies, Cornell University, Ithaca, NY 14853-5001

S. Bludman
Deutsches Elektronen-Synchrotron (DESY), D-22603 Hamburg, Germany

E. Swallow
Elmhurst College, Elmhurst, IL 60126

D. Smith
Embry Riddle Aeronautical University, Prescott, AZ 86301

S.N. Ahmed, V. Balbekov, G. Barenboim, L. Bartoszek, R. Bernstein
C. Bhat, D. Boehnlein, S. Brice, B.C. Brown, G. Drake
D. Finley, R. Ford, F. G. Garcia, N. Grossman, P. Kasper, E. Buckley-Geer
S. Childress, W. Chou, F. DeJongh, D. Elvira, S. Geer, D.A. Harris, J. Hylen
V. Klioukhin, T. Kobilarcik, I. Kourbanis, P. LeBrun, B. Lundberg
A. Malensek, A. Marchionni, W. Marsh, F. Mills, N. Mokhov, C. Moore, A. Moretti
J. Morfin, J. Nelson, D. Neuffer, P. Nienaber, A. Para, S. Parke, R. Plunkett, X. Qi
R. Raja, A. Romanino, A. Russell, P. Shanahan, P. Spentzouris, R. Stefanski
M. H. Shaevitz, W. Smart, N. Tobien, A. Tollestrup, A. Van Ginnekin, T. Williams
Fermi National Accelerator Laboratory, Batavia, IL 60510

L. Johnson
Grinnell College, Grinnell, IA 50112

M.D. Messier
Harvard University, Cambridge, MA 02138

M. Aoki, S. Ishimoto, Y. Mori, T. Yokoi, K. Yoshimura
High Energy Accelerator Research Organization (KEK), 1-1 Oho, Tsukuba-shi, Ibaraki-ken, 305-0801, Japan

E. Black, R. Burnstein, D. Kaplan, H. Rubin, Y. Torun, C. White
Illinois Institute of Technology, Chicago, IL 60616

M. Berger, C. Bower, D. Krop, G. Hanson, R. Heinz, S. Mufson
J. Musser, P. Schwandt, R. Tayloe
Indiana University, Bloomington, IN 47405

S. Striganov, V. Victorov
Institute for High Energy Physics, Protvino, Moscow, Russia 142284

I. Trostin
Institute for Theoretical and Experimental Physics, Moscow, Russia

A. Badertscher, A. Bueno, M. Campanelli, I. Gil-Botella
S. Navas-Concha, J. Rico, A. Rubbia
Institut fur Teilchenphysik, ETHZ, CH-8093, Zurich, Switzerland

J. Hauptman, J. Krane, K. Whisnant, B. Young
Iowa State University, Ames, IA 50011

L. Miller
James Madison University, Harrisonburg, VA 22807

M. Batouritski
Joint Institue for Nuclear Research, Dubna, Moscow region, Russian Federation

B. Blumenfeld, G. Domokos, S. Kovesi-Domokos
Johns Hopkins University, Baltimore, MD 21218

R. Rossmanith
Karlsruhe University, D-76128 Karlsruhe, Germany

B. Berger, D. Li, R. Rimmer, A. Sessler, M. Zisman
Lawrence Berkeley National Laboratory, Berkeley, CA 94720

V. Ryabov
Lebedev Physics Institute, Moscow, Russia

G. T. Garvey, W. C. Louis, G. B. Mills, V. Sandberg,
B. Sapp, R. Schirato, R. Van de Water, D. H. White
Los Alamos National Laboratory, Los Alamos, NM 87545

R. Imlay, A. Malik, W. Metcalf, M. Sung, M. Wascko
Louisiana State University, Baton Rouge, LA 70803

N. Longley
Macalester College, St. Paul, Minnesota

K. Scholberg
Massachusetts Institute of Technology, Cambridge, MA 02139-4307

C.P. Burgess
McGill University, Montreal, QC H3A 2T8, Canada

M. Berz
Michigan State University, East Lansing, MI 48824-1116

V. Palladino
Napoli University, Napoli, Italy

K. Anderson
New Mexico State University, Las Cruces, New Mexico Sunspot, New Mexico

H. Goldberg
Northeastern University, 111 Dana, Boston, MA 02115

C. Albright, G. Blazey, M-A. Cummings, A. Dychkant, D. Hedin
Northern Illinois University, DeKalb, IL 60115

A. Drabrowsky, T. Fonseca, H. Fox, S. Goy, S. Malik, V. Martin
R. Oakes, H. Schellman, M. Schmitt, M. Szleper, B. Van Rens, G. Unel
M. Velasco, G. Zeller
Northwestern University, Evanston, IL 60208

A. Skrinsky
Russian Acad. of Sci., Nucl. Phys. Dept., Novosibirsk

Y. Kuno
Osaka University, Osaka, Japan

C. Rott
Purdue University, West Lafayette, IN 47907-1396

A. O. Bazarko, K. T. McDonald, P. D. Meyers, F. C. Shoemaker
Princeton University, Princeton, NJ 08544

A. Belias
Royal Holloway and Bedford College, London, UK

T. Belias, P. Litchfield, K. Peach, G. Pearce, D. Petyt
Rutherford Appleton Laboratoty, Chilton, Oxon 0X11 OQX, UK

F. Olness
Southern Methodist University, Dallas, TX 75275-0175

L. Wai, S. Wojcicki
Stanford University, Stanford, CA 94305-4060

J. Hill, C.K. Jung, M. Malek, C. McGrew, I. Mocioiu
R. Shrock, C. Yanagisawa
State University of New York at Stony Brook, Stony Brook, NY 11794-3800

B. Acharya
Tata Institute, Bombay 400005, India

E. Tetteh-Lartey, B. Webb
Texas A&M University, College Station, TX 77843-4242

Y.F. Gu
Texas Tech University, Texas

A. Bogacz
Thomas Jefferson National Accelerator Facility Newport News, VA 23606

J. Ng
TRIUMF, Vancouver, BC V6T 2A3, Canada

T. Kafka, T. Mann, M. Sanchez, J. Schneps
Tufts University, Medford, MA 02155

I. Stancu
University of Alabama, Tuscaloosa, AL 35487

S. Iyer
University of Arizona, Tucson, AC 85721

C. Andreopoulos, N. Giokaris, G. Mavromanolakis, N. Saoulidou, G. Tzanakos
University of Athens, 15771 Athens, Greece

J. Wurtele
University of California, Berkeley, CA 94720

J. Gunion
University of California, Davis CA 95616-8677

D. Casper, W.R. Kropp, D. Silverman, H. Sobel
University of California, Irvine, CA 92697

D. Cline, K. Lee, C. Matthey, S. Otwinowski, Y. Seo, F. Sergiampietri
H. Wang
University of California, Los Angeles, CA 90095-1547

E. Church, G. J. VanDalen
University of California, Riverside, CA 92521

M. Thomson
University of Cambridge, Cambridge, UK

E. Gates, K. Hoffman, K-J. Kim, M. Oreglia, Y. Wah, U.K. Yang
University of Chicago, Chicago IL 60637

E. Hawker, R. A. Johnson, J.L. Raaf, N. Suwonjandee
University of Cincinnati, Cincinnati, OH 45221

A. Blondel
University de Geneve, CH-1211 Geneve 4, Switzerland

A. Kibayashi, J.G. Learned, J. Maricic, S. Matsuno, R. Milincic
S. Pakvasa, M. Rosen, D. Takemori
University of Hawaii, Manoa, 2505 Correa Road, Honolulu, HI 96822

D. Errede, G.D. Gollin, K. Makino
University of Illinois at Urbana-Champaign, Urbana IL 61801-3080

Y. Onel
University of Iowa, Iowa City, IA 52242-1479

B.P. Roe
University of Michigan, Ann Arbor, MI 48109

D. Demuth
University of Minnesota, Crookston, Minnesota

A. Habig
University of Minnesota, Duluth, MN 55812

M. DuVernois, H. Gallagher, K. Heller, M. Marshak, E. Peterson
K. Ruddick, J. Urheim
University of Minnesota, Minneapolis, MN 55455

L. Cremaldi, V. Eschenburg, D. Sanders, D. Summers
University of Mississippi, University, MS 38677

P. Depommier
University of Montreal, Montreal, Canada

M. Lindner
University of Munich, Munich, Germany

B. Bassalleck, N. Bruner, D.E. Fields, M. Gold, T. Thomas
University of New Mexico, Albuquerque, NM 87131

J. Cobb, A. DeSanto, A. Weber, G. Barr
University of Oxford, Keeble Road, Oxford, Oxon, OX1 3RH, UK

R. Brugnera, L. Stanco
University of Padova and INFN, Padova, Italy

J. McDonald, D. Naples, V. Paolone
University of Pittsburgh, Pittsburgh, PA 15260

S. Avvakumov, A. Bodek, H. Budd, P. deBarbaro, K. McFarland
University of Rochester, Rochester, NY 14627

T. Bergfeld, A. Godley, S. Mishra, C. Rosenfeld, K. Wu
University of South Carolina, Columbia, SC 29208

E. Falk Harris, P. Harris
University of Sussex, Falmer, Brighton BN1 9QJ, UK

H.-J. He, S. Kopp, K. Lang
University of Texas at Austin, Texas 78712-1081

W. Leeson
University of Texas Pan American, Edinburg, TX 78539-2999

J. Matthews
University of Utah, Salt Lake City, UT 84112-0830

J. Wilkes
University of Washington, Seattle, WA 98195-1560

A.B. Balantekin, V. Barger, A. Erwin, D. Marfatia, B. Wood
University of Wisconsin, Madison, WI 53706

J. W. F. Valle
IFIC-Instituo de Fisica Corpusclar, CSIC-University of Valencia, Valencia, Spain

T. Weiler
Vanderbilt University, Nashville, TN 37235

C. Hagner
Virginia Tech., Blacksburg, VA 24061

L. Barrett
Western Washington University

D. Fields
Yale University, New Haven, CT 06520-8121

S. Menary
York University, Toronto, Ontario M3J 1P3, Canada

1 Introduction

Neutrino oscillation physics has entered a very exciting period. The atmospheric muon-neutrino deficit measurements from the Super-Kamiokande (Super-K) experiment provide convincing evidence for lepton–family number violation. The Super-K data suggest that the deficit is due to $\nu_\mu \rightarrow \nu_\tau$ oscillations with an oscillation amplitude that corresponds to maximal (or near-maximal) mixing, and an oscillation frequency that corresponds to a difference between the squares of the masses of the participating neutrino mass eigenstates given by $\delta m^2_{atm} \sim 0.003$ eV^2. Oscillations with these parameters are within reach of the present generation of long baseline accelerator-based experiments!

In addition to the exciting atmospheric neutrino results, there are other possible indications for neutrino oscillations driven by very different δm^2 scales: namely, the solar neutrino deficit and the evidence for $\nu_\mu \rightarrow \nu_e$ oscillations from the LSND experiment. In the next few years the accelerator and non-accelerator experiments that are currently running, or are under construction, are expected to (a) confirm the oscillation interpretation of the atmospheric neutrino deficit, (b) clarify whether the apparent deficit of electron neutrinos coming from the sun is also due to oscillations, and (c) confirm or otherwise the oscillation result from the LSND experiment. Although the new experiments will address these initial issues, they will also leave many basic questions unanswered. A further generation of neutrino oscillation experiments will be required to more fully understand the framework and parameters that describe lepton–family number violation.

We would like to express our interest in a neutrino physics program in the era beyond MINOS and MiniBooNE. In principle this long–term program could be at Fermilab, Brookhaven, or at a location outside of the US (e.g. CERN or JAERI). Fermilab is currently the center for the ongoing US accelerator-based neutrino program. We encourage the laboratory to support those studies and R&D activities needed to ensure that there is a cutting-edge neutrino oscillation program beyond the next few years.

2 Present status and future expectations

At present there are several viable regions of oscillation parameter space that are consistent with the observed solar neutrino deficit, but all of these regions require $\delta m^2_{sol} \lesssim 10^{-4}$ eV^2, much smaller than δm^2_{atm}. The viable LSND region of parameter space requires $\delta m^2_{LSND} \gtrsim 0.3$ eV^2, much larger than δm^2_{atm}. We know of three neutrino flavors, but three-flavor mixing can only accommodate two δm^2 scales. Hence, either there are more (sterile) flavors to be discovered, or else the solar neutrino deficit is not due to oscillations and/or the LSND result is not due to oscillations.

Before we can begin to understand the framework within which lepton–family number violation is taking place, we must first confirm (or otherwise) the $\nu_\mu \rightarrow \nu_\tau$ interpretation of the atmospheric neutrino deficit, and clarify whether the LSND and solar neutrino results are due to oscillations. These are the goals for the next generation of accelerator and non-accelerator based experiments.

We can anticipate that the present generation of long baseline experiments (K2K, MINOS, OPERA, ICARUS) will confirm that $\nu_\mu \rightarrow \nu_\tau$ oscillations partly or fully explain the atmospheric neutrino deficit, and that the associated oscillation amplitude and δm^2 will be measured with precisions of $\sim$ 10%. We can also anticipate that the MiniBooNE experiment will confirm or reject the oscillation interpretation of the LSND results, and if LSND is confirmed, measure the associated amplitude with a precision of $\sim$ 10%, and δm^2 with a precision of ~ 0.1 eV^2. Finally, data from SNO, KamLAND, and Borexino, together with further Super-K measurements, will very likely leave us with either one region of viable parameter space for solar neutrino oscillations, or perhaps rule out all regions of parameter space. Hence, within a few years, we expect much progress in clarifying which phenomena are due to oscillations, and which regions of parameter space are viable. However, the experiments will leave many unanswered questions:

(i) Is three-flavor mixing the whole story, or is the phenomenology more complicated (sterile neutrinos, neutrino decay, extra dimensions ...)?

(ii) How large are each of the entries in the neutrino mixing matrix? Within a three-flavor mixing framework, we expect to have a reasonable measurement of one (possibly two) mixing angle(s), but only poor knowledge of (or limits on) the other angle(s), and no knowledge of the phase. If it's not three-flavor mixing, then understanding the rank of the mixing matrix will be an open question that may need to be answered before we can make sense of any of the mixing parameters.

(iii) Is there significant CP violation in the lepton sector? CP violation may be large enough to be measured if either the LSND result is confirmed, or if the solar neutrino deficit is due to oscillations with parameters that correspond to the Large Mixing Angle MSW solution, which is one of the presently favored regions of parameter space.

(iv) What does the neutrino mass spectrum look like? Within the three-flavor mixing framework we will know the magnitude of one (possibly both) of the two δm^2 scales, but not their sign(s). Hence, there will be an ambiguity in our knowledge of the pattern of neutrino masses.

If the next generation of experiments produces one or more surprises, other pressing questions may be added to this list. However, no matter what happens, it is our expectation that answers to the very basic questions listed above, together with more precise measurements of the parameters δm^2_{32} and $\sin^2 2\theta_{23}$, will require a new generation of detectors and beams beyond the next generation of experiments.

3 Studies and R&D

There are significant activities in the US, Europe, and Japan to design and develop the technology for upgraded conventional neutrino beams, and for neutrino factories. In the US the R&D is being pursued by a collaboration of about 140 particle and accelerator physicists from laboratories and Universities. Fermilab has a very active group within this collaboration, and has participated in two neutrino factory design studies. The first of these was a 6 month design study [1] initiated at Fermilab. The second study is currently being completed at Brookhaven [2]. In addition, there have been recent studies at Fermilab that have explored the physics capabilities at neutrino factories [3] and at upgraded neutrino beams [4]. These studies have been conducted with the participation of physicists from Universities and other laboratories. There are also ongoing brighter booster physics [5] and design [6] studies. In the longer term there will need be a process that (a) identifies any remaining promising possibilities that merit further study, and (b) uses the results of all of the studies to formulate a proposal for a long term neutrino physics program. Some tentative conclusions reported from the studies so far are:-

Independent of whether the solar neutrino deficit and/or the LSND observations have anything to do with oscillations:

(i) An upgraded conventional neutrino beam produced using an ~ 1 MW brighter booster, or using a MI beam with ~ 4 times the present intensity, would enable $\nu_\mu \to \nu_e$ oscillations driven by the δm^2_{atm} scale to be observed provided the associated oscillation amplitude parameter ($\sin^2 2\theta_{13}$) is not smaller than about 0.003. This value is an order of magnitude below the range we expect to be probed by MINOS and the CNGS experiments.

(ii) A neutrino factory would enable $\nu_e \to \nu_\mu$ oscillations driven by the δm^2_{atm} scale to be observed provided the associated oscillation amplitude parameter ($\sin^2 2\theta_{13}$) is not smaller than O(0.0001). This value is about two orders of magnitude below the range we expect to be probed by MINOS and the CNGS experiments.

(iii) If a $\nu_\mu \to \nu_e$ signal is observed at a conventional neutrino beam, or a $\nu_e \to \nu_\mu$ signal is observed at a neutrino factory, further long-baseline measurements would enable the determination of the sign of δm^2_{atm}, and hence the pattern of neutrino masses.

Within the framework of three-flavor mixing with the δm^2 scales given by δm^2_{atm} and δm^2_{sol}:

(iv) Even if $\sin^2 2\theta_{13}$ is zero, a $\nu_e \to \nu_\mu$ signal might be observed at a neutrino factory if $\sin^2 2\theta_{12}$ and δm^2_{sol} are not too small, with the signal arising from oscillations driven by the solar neutrino deficit scale. This would provide a unique accelerator based measurement of δm^2_{sol}, and the amplitude parameter $\sin^2 2\theta_{12}$.

(v) If the Large Mixing Angle MSW solution describes the solar neutrino deficit, a search for CP violation would be viable at a neutrino factory for a significant region of oscillation parameter space. A search for CP violation might also be viable at a neutrino beam driven by a brighter booster, but only over a very limited region of parameter space.

If the LSND oscillation results are confirmed:

(vi) A search for CP violation would be viable over a significant region of parameter space at a low intensity neutrino factory.

(vii) $\nu_\mu \to \nu_\tau$ and $\nu_e \to \nu_\tau$ searches at the LSND δm^2 scale would be exceptionally interesting, and would therefore place a premium on ν_τ appearance. This would benefit from a detector R&D program.

(viii) If the solar neutrino deficit is also due to oscillations, then we will have the exciting prospect of at least three δm^2 scales, the phenomenology may be complicated, and we will require many measurements to understand the oscillation framework and parameters.

Finally, there is also an interesting non–oscillation neutrino physics program that can be pursued exploiting the very intense neutrino beam just downstream of a neutrino factory. With four orders of magnitude improvement in intensity compared with existing neutrino beams, very high precision high granularity low mass neutrino detectors become feasible. This would facilitate precise measurements of flavor– and spin–dependent parton distributions, studies of parton distributions in a nuclear environment, tagged heavy quark production measurements, new measurements of electroweak and strong interaction parameters, and searches for a variety of exotic phenomena.

Encouraged by the results of these initial physics studies, we believe that the international activities devoted to designing and developing the technology required for upgraded conventional neutrino beams, and for neutrino factories, are well motivated. At Fermilab there are very active groups involved in the facility design, component R&D, and the complementary physics studies. These groups collaborate with equally active groups at BNL, LBNL, and at Universities throughout the US. Although much progress is being made with the limited available resources, the R&D program requires increased support if a neutrino factory is to be a viable option when it will be needed, sometime in the next decade.

4 Summary

Fermilab is currently the home of the ongoing accelerator-based neutrino oscillation program in the US, and is well positioned to support an extended neutrino physics program in the era beyond the present experiments. It is too early to propose a detailed experimental program. However, to provide the right facilities at the right time will require strong support for (a) continued physics studies and facility design studies, (b) facility R&D, and (c) detector R&D.

We would like to express our interest in a neutrino physics program in the era beyond MiniBooNE, MINOS, K2K, and the CNGS experiments. We believe that the physics of lepton–family number violation is exciting, and encourage the laboratory and funding agencies to invest in preparing a long term future for neutrino oscillation experiments, independent of where those experiments might eventually be located.

References

[1] N. Holtkamp and D. Finley (editors) "A feasibility study of a neutrino source based on a muon storage ring", Report to the Fermilab Directorate, FERMILAB-PUB-00-108-E, http://www.fnal.gov/projects/muon_ collider/nu-factory/nu-factory.html

[2] Neutrino factory design study report, in preparation.

[3] S. Geer and H. Schellman (editors) "Physics at a Neutrino Factory", Report to the Fermilab Directorate, FERMILAB-FN-692, April 2000., hep-ex/0008064.

[4] V. Barger et al., "Oscillation measuremenets with upgraded conventional neutrino beams", hep-ph/0103052.

[5] Physics at an upgraded Fermilab Booster, report in preparation.

[6] W. Chou, C. Ankenbrandt, E. Malamud (editors) "The Proton Driver Design Study", FERMILAB-TM-2136, December 2000.